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Modelling of energy demand in a modern domestic dwelling

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Abstract

The domestic building sector accounts for 13% of the total UK greenhouse gas emissions. In order to curtail the emissions, implementation of higher insulation materials in building envelopes and integrated low carbon technologies within buildings becomes an alternative solution. Space heating energy demand in different types of domestic dwellings was modelled. Based on the occupancy pattern, the appliance and lighting schedule were obtained for calculating electrical demand. Two new build homes in Corby representing current and future dwellings were investigated to compare the difference of energy demand.

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Keyworks: Building energy modelling, Energy demand, Future domestic dwellings.

1. Introduction

Climate change and global warming has been gradually drawn attention by public these years, and Britain, has committed a legally binding carbon targets to cut greenhouse gas (GHG) emissions 34% by 2020 and at least 80% by 2050 compared to 1990 level [1].

Looking at the GHG emissions of today, the domestic building sector accounts for 13% of the total UK emissions, and it is supposed to provide a significant contribution to the emissions targets which is almost zero by 2050 [1]. In order to realise this target, appropriate design and planning of new build domestic dwellings to curtail emissions is necessary. One approach is to utilise improved construction and material to drive higher energy efficiency of the building envelope. However, achieving significant emission reductions by only employing the improved building fabric is expensive and not sufficient. Therefore, the deployment of integrated low carbon technologies within dwellings becomes an alternative solution. Kelly et al. [2] investigated the combined heat pump and household appliance electrical demand over 24 hours based on typical UK detached dwellings. Richardson et al. [3] investigated a domestic electricity demand model with detailed occupant behaviour and appliance schedule.

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The purpose of designing and constructing a building is to make it comfortable for people living, and to make it to be energy efficient. Figure 1(a) explains the general procedure of the building energy modelling, where the energy required from the heating system is the major part in the whole building energy flows.

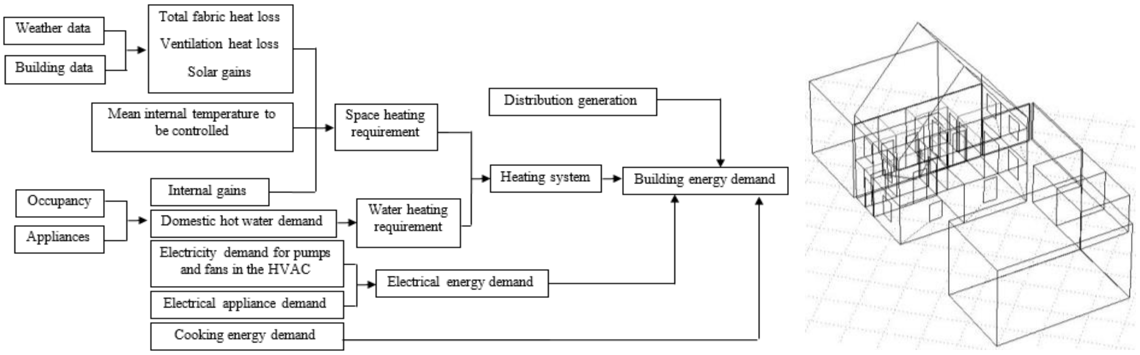

Fig. 1. (a) The flowchart of the building energy modelling procedure; (b) The configuration of Corby homes in ESP-r.

2. Future domestic dwellings

2.1. Characteristics of future domestic dwellings

The future domestic dwellings aim to reduce carbon emissions through increased energy efficiency. It can be implemented through raising building fabric efficiency. Major improvement includes reducing thermal bridging, increasing the air tightness and reducing the U values of building elements. The U value is a measure of heat loss in a building element and derived from thermal resistances of building materials. It denotes how effective a material is, the higher the U value the worse the thermal performance of buildings. Through changing building materials or adding insulation can improve the U value.

2.2. Utilization of low carbon technologies in dwellings

A number of low carbon technologies are available to be utilised for domestic dwellings to accomplish zero carbon target. Solar photovoltaic (PV) is one widely used renewable energy generation technology, and it has already been installed 1931MW in UK by Mar. 2014 [4]. Photovoltaic thermal (PVT) combines two technologies: PV and solar thermal, which work against each other. PV generates electricity from solar module which increases the temperature of the cells resulting in a significant fall of electricity generation efficiency [5]. However, the solar thermal module in PVT removes waste heat from the PV module and cools it down to a more efficient mode by using a circuit of fluid travelling around the panel. Heat pump is a device that transfers thermal energy from a heat source such as air, ground or water to another destination such as hot water and space heating in domestic dwellings. The coefficient of performance (COP) represents the energy efficiency of a heat pump which depends on the temperature difference between the heat source and the heat emitter. The smaller the temperature lift the higher the energy efficiency and COP. When the PVT system is integrated with a water to water heat pump, the generated thermal energy can be used as a part of heat sources fed into the heat pump to minimise the temperature difference. Bakker et al. proposed a system using PVT combined with a ground coupled heat pump which was nearly able to satisfy all the heating demand [6].

3. Building energy modelling tool

There are quite a few building energy modelling programmes which have been developed. Based on the heat and mass balance equations, given climate data, building geometry information and relevant plant systems with control strategies, the programmes can provide a time step calculation of building energy flows. In this study, ESP-r (Environmental System Performance Research programme) is used as the programme for modelling.

ESP-r is an integrated building simulation software which commits to capture the dynamic behaviour and interaction of building systems, and strives to model all relevant physical processes, encompassing heat transfer, air flow, electric power flow and heating, ventilation and air conditioning (HVAC) system. A finite difference approach based on a control volume heat balance is employed in ESP-r to represent all relevant energy flows by establishing thermal states equations of discretized building systems.

The conservation equations for each node considering any energetic contact can be interpreted as ensuring that the rate of storage of a transport property within the control volume is equal to the net flux of such a property across the control surface plus the portion of the property generated within the volume [7]. Consider a control volume P is bounded by a control surface, the conservation equation is expressed in (1) [7], and other energy conservation equations are explained in [8].

$$\frac{\partial}{\partial t}(\rho_P \upsilon_P \phi_P)=\sum_{j=1}^{n} K_{j,P}(\phi_j-\phi_P)+S_{\phi_P}\upsilon_P \tag{1}$$

Φ is a transport property such as temperature etc., ρ_p is the density of the region P, υ_p is the volume of the region P, $S_{\phi p}$ is any energy or mass injected directly to the finite region. As the flux at the control surface is normally hard to define, a function of the transport property differences is used instead which $K_{j,p}$ is the conductance coefficient between volumes j and P.

At each finite period of time the algebraic energy conservation equations are established and written in a matrix as shown in (2) [7],

$$\left[A(T)\right]\left[T\right]=\left[B(T)\right] \tag{2}$$

T is a vector of unknown nodal temperatures and heat injections, A is a non-homogeneous sparse matrix consisting of the future time-row coefficients, and B is the matrix corresponding to the present values and the known boundary vectors at the present and future time rows. Then a direct solution method is applied to simultaneously solve the energy equations of each building zone and plant at each simulation time-step.

4. Modelling of energy demand of Corby homes

Electric Corby, constructed 10 new homes, including 3 types: 2 control homes, 4 gas homes and 4 electric homes. In this study, two types of dwellings, control homes and electrical homes, are selected to represent the current dwelling and future dwelling for comparing the differences in building energy demand, and detailed construction information of two homes are shown in Table 1.

Table 1. Construction of Control home and Electrical home.

Type of home	Build	Energy source
Control home	Standard build, UK code level 3, 85m^2 Putney plus	Gas fired central heating and solar thermal panel
Electrical home	Same as Putney plus, except for greater wall thickness higher insulation and improvement in U values	Loft mounted heat pump and PVT panels

In order to model the energy demand of Corby homes in ESP-r, each dwelling was constructed through setting corresponding coordinates from floor plans, and the material required with different U values of constructions was derived from the material database inside ESP-r. Considering the realistic impact of the solar gains on dwellings, the model of Corby homes was surrounded by adjacent dwellings and trees which were represented by cubes consequently as shown in Figure 1(b). Besides building construction data, climate data is another crucial factor in the modelling. The climate data used in modelling contains the wind speed, solar radiation and ambient temperature and was derived from ESP-r climate database.

Domestic hot water (DHW) can be calculated considering many factors such as the volume requirement per person and required water temperature etc. Yao et al. indicated that 6.8 kWh/day was used for DHW of a three per family [9], which was adapted to the modelling of building energy demand by timing the occupancy affection index. For each Corby home, it was assumed to be 2 occupants dwelling, hence, the energy demand for DHW was 4.4 kWh/day.

Internal heat gains, as the hourly time-step inputs, have significant effects on modelling. It depends on the occupants' behaviour, lighting and appliance schedules, which were obtained from [2][3]. Unit internal heat gains of occupants were derived from [10], encompassing 75W sensible heat and 45W latent heat for active occupancy, while 60W sensible heat and 45W latent heat for sleeping occupancy. The occupancy pattern utilised was taken from UK time-use survey data [2]. On weekdays the occupants are assumed to be active between 7-9am and 5-11pm and sleeping between 11pm-7am, from 9am to 5pm, the dwelling is assumed to be unoccupied. During weekends and holidays, active periods are 8am-10am and 4pm-midnight, the sleeping occupancy is assumed to be from midnight to 8am, for the time between 10am and 4pm, it is assumed that occupants are involved in other activities out of the dwelling. Lighting and appliance schedule approximately follow and vary with the occupancy pattern.

Infiltration, also referred as air leakage, is the process of internal warm air exchanged with the fresh and cold external air through cracks and openings. Ventilation is the same process but within the building itself. The control home was set to 0.6 air change per hour (ACH) of the infiltration rate, while 0.5 ACH was set for electrical home in the ESP-r modelling due to the higher insulation material in the constructions. Additionally, the kitchen and bathroom were set to 3.5ACH and 7ACH respectively according to the active occupants' behaviour. When the temperature in each room exceeds 24ºC, the air change rate is increased to 4ACH to represent the natural ventilation procedure.

The heating schedule in ESP-r modelling was implemented as that 7am-9am and 4pm-11pm for weekdays, 7am-11pm for weekends and internal heating temperature sets were based on the previous studies [11] which 21ºC and 19ºC were used for living rooms and other rooms respectively.

5. Results and discussion

5.1. Electricity consumption according to the occupancy pattern

According to the occupancy pattern employed, the electricity consumption from lighting and appliances, as shown in Figure 2(c), was conducted by drawing the electrical power of each individual appliance from [3]. It illustrates the distribution of electricity consumption along 24 hours separated into weekdays and weekends, and it also clearly indicates that the peak electricity demand occurs around 8-9am and 7-9pm for every single day. Consequently, the total electricity consumption for a whole year of each Corby home was approximately 4323kWh.

5.2. Space heating demand in Corby homes

The space heating is one of the dominant energy demands and it is mainly determined by the size of the dwelling, heat transfer coefficient, temperature difference and the heat gains.

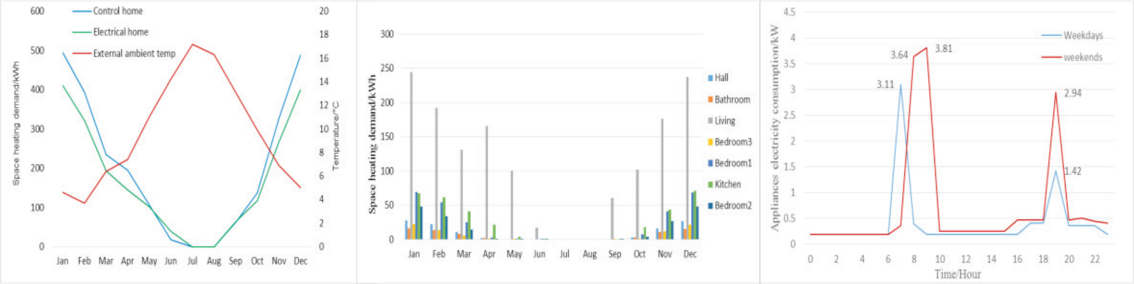

Fig. 2. (a) Space heating demand against external temperature; (b) Space heating demand distribution in Control home; (c) Appliance electricity consumption of each individual Corby home

According to the modeling from ESP-r, the space heating demand is 2452.2 kWh/year for control home and 28.8kWh/m^2, 2055.9 kWh/year and 24.2kWh/m^2 for electrical home. The space heating demand of an electrical home is lower than that of a control homes, which is an expected result due to higher insulation material employed in electrical home. In Figure 2(a), it shows the monthly space heating demand against average external ambient temperature. It can be seen that a higher space heating demand is required for control home, and no demand during summer period. A living room is in need of the most heating demand of the whole dwelling as shown in Figure 2(b).

5.3. Overall energy demand in Corby homes

The electrical and thermal generation from PVT and solar thermal system in Corby homes were derived through PV-sol and T-sol, which are the design programmes for simulating PV performance and solar thermal system. It gave 2954kWh/year for electrical generation and 1902kWh/year for thermal generation which considered the facing direction and location of the dwellings. The heating system efficiency was considered when calculating the overall energy demand of each dwelling, which 0.9 is counted as for gas boilers in control homes and 4.5 COP is utilised for water to water heat pumps in electrical homes. Results show that, the overall energy demand is 6378.9kWh/year in a control home and 2114.8kWh/year in an electrical home which is significantly reduced.

5.4. Sensitivity analysis

In order to quantify the energy demand of Corby homes under different conditions, four scenarios were investigated. The detailed scenarios information and overall energy demand are shown in Table 2. With occupants' effective thermostatic control in dwellings the overall energy demand for each type of homes is significantly reduced. Compared with the normal operation condition, the overall energy demand in an electrical home was reduced by 8.7%.

Table 2. Overall energy demand for four different scenarios of Corby homes

Scenarios	Extreme winter	No control	Good control	Home office
Description	A winter week used the highest energy for space heating was applied to all winter weeks with same heating schedule and internal heating temperature sets.	No thermostatic control made by occupants with same heating schedule but 21ºC internal heating temperature for all rooms.	Thermostatic control is made by occupants and achieved by setting 18ºC internal heating temperature for bedrooms, kitchens and study rooms on weekends,17ºC for bathroom, halls and second bedrooms and 20ºC for living rooms.	One person was active from 9am to 5pm at home and with the same heating schedule except for study rooms with 21ºC from 9am to 5pm and 19ºC from 5pm to 11pm, and living rooms are heated to 19ºC between 7am and 11pm during weekdays.

Overall energy demand (kWh/year)	Control home	Electrical home	Control home	Electrical home	Control home	Electrical home	Control home	Electrical home
	8487.5	2264.9	6707.5	2186.0	5227.5	1930.6	6019.7	2037.1

6. Conclusion

In this paper, modelling energy demand in the domestic dwellings was carried out through a bottom up approach, which is based on the occupancy pattern, lighting and appliance schedule. Two new build homes in Corby representing current and future dwellings were investigated. Comparing current dwellings, the overall energy demand is dramatically reduced in future dwellings, additionally, with occupants' effective thermostatic control, it can be further reduced by 8.7%.

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Reference

[1] HM Government. 2009. UK Low carbon transition plan. [Online]Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/228752/9780108508394.pdf [Accessed 24 November 2014].

[2] Kelly NJ, Tuohy PG, Hawkes AD. Performance assessment of tariff-based air source heat pump load shifting in a UK detached dwelling featuring phase change-enhanced buffering. Applied Thermal Engineering. 2014;71:809-20.

[3] Richardson I, Thomson M, Infield D, Clifford C. 2010. Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings*,*42*(10), pp.1878-1887.

[4] Department of Energy & Climate Change. 2014. Weekly solar PV installation & capacity based on registration date. [Online]Available at https://www.gov.uk/government/statistical-data-sets/weekly-solar-pv-installation-and-capacity-based-on-registration-date [Accessed 29 November 2014].

[5] Tripanagnostopoulos Y, Nousia Th, Souliotis M, Yianoulis P. Hybrid photovoltaic/thermal solar systems. Solar Energy. 2002;72(3):217-234.

[6] Bakker M, Zondag HA, Elswijk MJ, Strootman KJ, Jong MJM. Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump. Solar Energy. 2005;78(2):331-339.

[7] Negrao COR. Conflation of computational fluid dynamics and building thermal simulation. Ph.D. Thesis, University of Strathclyde, Glasgow, UK, 1995.

[8] Clarke JA. *Energy simulation in building design.* 2nd ed. Oxford: Butterworth-Heinemann; 2010.

[9] Yao, R., & Steemers, K. 2005. A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings*, *37*(6), pp.663-671.

[10] CIBSE 2006 Guide A-Environmental design. CIBSE London.

[11] Shipworth M, Firth SK, Gentry MI, Wright AJ, Shipworth DT, Lomas KJ. Central heating thermostat settings and timing: building demographics. Building Research & Information. 2010; 38:50-69.